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**SOLAR DIAMETER MEASUREMENTS FOR STUDY OF
SUN CLIMATE COUPLING**

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Preface

This project was initiated to detect variability in solar shape and diameter as a possible probe of an important climatic driving function, solar luminosity variability. The techniques and facilities developed at SCLERA¹ during the 1970's for measuring the solar diameter were used. During the contract period the observing program for this project was begun, as was the requisite data reduction. These two activities were conducted simultaneously. The success of the observing program over long time periods depends in part on the development of a technique to calibrate the scale in the telescope field, and work on this progressed to the design and construction phase.

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¹SCLERA is an acronym for the Santa Catalina Laboratory for Experimental Relativity by Astrometry, a facility jointly operated by Wesleyan University and the University of Arizona.

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1. History

The detection and monitoring of climatically significant changes in the solar constant has been the goal of many researchers (for review, see White 1977; Pepin, Eddy and Merrill 1980; Sofia et al. 1979; Gough 1980; Kandel 1981). One indirect diagnostic of luminosity changes employs the study of changes in the solar shape and diameter. Because of the advances made at SCLERA during the 1970's in the accurate measurement of solar diameters, studies of the solar figure and diameter may offer a method of probing this important climatic driving function which is more sensitive and cost-effective than direct measurement.

The improvements in solar diameter measurements have been made possible by the utilization of an astrometric telescope designed solely for work relating to the sun and by the introduction of a new technique for the definition of an edge on the solar limb. This work at SCLERA has allowed measurement of solar diameters with accuracies of $\Delta D/D \sim 10^{-5}$ to 10^{-6} . Oleson et al. (1974) give a description of the telescope used in SCLERA's work; papers by Hill, Stebbins and Oleson (1975) and Hill (1978) contain discussions of the edge definition.

The accuracy currently obtainable in measurements of changes in the solar diameter has been reported to be $\Delta D/D \approx 2 \times 10^{-6}$. This value may be compared to the accuracy found in direct luminosity measurements over a period of years to decades, which currently stands at $\Delta L/L \sim 10^{-3}$. This comparison, together with the prospects for obtaining such accuracy over long time periods, provide a rationale for the use of solar diameter measurements to study long-term solar variability.

2. Progress to Date

It was necessary to extend the capabilities of the solar diameter measuring program at SCLERA to make possible the detection of long-term changes. The solar detector developed during the 1970's was capable of observing solar diameter changes having periods less than or equal to a few hours with an accuracy of $\Delta D/D \sim 10^{-5}$ to 10^{-6} . For the study of climatically significant changes, which have periods of years to decades at the short period end of the power spectrum, the stability of the telescope must either be properly maintained or the lack of stability monitored and corrected for. In addition, the basic measuring engine in the focal plane, an interferometer, must be capable of stability over this period range. In order to meet these requirements as well as to respond to the desire to have the relevant observations commence as soon as possible, two parallel efforts were launched to extend the period of stability. One exercise was designed to be a short-term solution to permit the observational program to start as soon as possible while the second exercise was designed to lead to a long-term solution.

With the implementation of the short-term solution for telescope and measuring engine stabilization, the observational phase was begun. Starting in March of 1981, observations were made, weather permitting, and analysis of the data begun. The work described has been reported in four invited papers and one contributed paper. Two papers have also been submitted to the Astrophysical Journal for publication.

2.1. Short Term Stabilization of Telescope

The solar astrometry which forms the basis of this study of solar diameter changes requires that systematic errors arising from the telescope be $\leq 10^{-6}$ of the solar diameter over extended time periods. It is in general quite difficult to bring an observing instrument to such a standard if the instrument was not originally designed with this in mind. However, this was not the difficult aspect of the problem because the SCLERA telescope was engineered to meet even tighter criteria (Oleson et al. 1974). This standard could be met by "freezing" the configuration of the system. However, this would effectively halt implementation of technical advances in the observational work. This restriction motivated the development of a calibration system which could be used in lieu of permanently freezing the configuration of the telescope.

With the probability of the development of an adequate calibrating system in a relatively short period of time, the short-term solution to the stabilization of the telescope was implemented by placing the telescope configuration in a frozen state. This in large measure was achieved simply at the administrative level: as of a certain date, there would be no more changes in the telescope and solar detector until the calibrating system was on-line. However, a few mechanical operations were necessary to help insure the success of the short-term solution. The solar detector itself had been in a rather exposed position, leaving open the very likely possibility of accidental bumps by personnel, and the interferometer optics in the focal plane measuring engine were by

design free to be adjusted. Neither of these situations were consistent with the stability requirements. Consequently, a protecting shield was built around the solar detector and the relevant interferometer optics were cemented down. In addition, all of the adjustments in the system were set to optimize performance before freezing the telescope configuration.

All phases leading to the implementation of the short-term solution have now been completed.

2.2. Short-Term Stability of the Focal Plane Measuring Engine

In contrast to the traditional observing scheme in astrometry where the information in the focal plane is recorded on photographic plates and the distances between points on these plates is then measured by an engine off-line, the SCLERA system has the measuring engine located in the focal plane and measures distances between images directly. This measuring engine is a Michelson interferometer augmented to use two 6328 Å He-Ne laser beams which are 90° out of phase. This allows for direct recording of changes in the optical paths of the two legs of the interferometer and thus changes in the distances between images (the use of only one beam can tell that a path change has occurred but cannot in itself indicate the direction of the change).

All solar oblateness and solar oscillations studies at SCLERA have used this interferometric measuring engine. For these prior studies, it was only necessary to detect changes in diameter that occurred during any one day. The stability of the interferometer system was such that it could be simply turned on each observing day and relative changes recorded during that day. However, operation in this relative mode is not adequate for longer time periods because of power failures, laser plasma tube failure, etc. A resolution to this problem was to use the white light fringe in the interferometer to locate the laser beam fringe that corresponds to equal paths in the two legs of the interferometer.

Much work had been done at SCLERA on the incorporation of such a white light fringe feature to operate simultaneously with the dual laser beam (Smolka, Brown and Hill 1976). The interferometer was designed to receive such an addition. During this contract, the implementation of the white light fringe mode was effected and the system is now operational. Hardware was also added to the system to aid in localizing the white light fringe.

It should be noted that this feature is essential to the maintenance of stability in both the short-term and long-term modes of operation. In the short-term mode of operation without the white light fringe as a fiducial, the interferometer simply must not fail; in the long-term mode, it is much easier to locate the position of the white light fringe than to execute an absolute calibration of the system.

2.3. Observations

An observing program to detect long-term solar variability requires a more intensive use of the observational facilities than was necessary for the earlier work at SCLERA. The staff during the earlier period was quite small in number and most activities had to be performed in a serial rather than a parallel mode. That is, observations would be made for a period of time, then the observing program would be shut down and the data analysis begun. Because of the complexity of data reduction and because of the attention that the new results received outside SCLERA, this data analysis period was usually much longer than the time required originally for the observations themselves. However, in order for a long-term solar variability program to make any significant contributions, observations have to be made as continuously as possible over long periods of time.

A parallel mode of operation had to be instituted, allowing simultaneous data acquisition and data analysis. It was therefore necessary to enlarge the number of staff members and to train them in the operation of the telescope. During the implementation of the short-term solution to the maintenance of telescope stability, additional observing staff members were trained. This training phase has reached the stage where the new people can contribute to the observing program.

Starting in March of 1981, observations were made, weather permitting. The weather this year was unseasonably bad for observation. A log of weather conditions at the telescope site was maintained from February 1981 through the end of the contract period (see monthly reports submitted to NASA-Goddard Space Flight Center). This log shows, unfortunately, that only approximately 24% of the days were sufficiently clear to permit observations for an extended time. In addition, some of these clear days were not available to the solar program because of the demands of the experimental relativity program or because of equipment failures. Overall, approximately 12% of the days during this four-month period could be used for data acquisition for the solar program. However, the observational program was put into operation and a limited amount of data taken.

2.4. Data Analysis

The staff expansion reported in Section 2.3 allowed simultaneous acquisition and reduction of data for the first time at SCLERA. Although the amount of data acquired was quite small, analysis was begun, introducing the new staff to the meticulous task of data reduction and initiating a preliminary evaluation of the systematic errors arising from the telescope as currently configured.

The purpose of the initial data analysis was to identify systematic errors arising in the telescope system itself. During the winter of 1980, preparations for the planned freezing of the telescope's configuration necessitated the realuminization of the elevation and azimuth tracking mirrors and the replacement of the window which separates the optics from the external weather. During the same period, the solar detector

was also modified so that the detectors for the telescope's primary tracking system and the slits used to define the edge of the sun were coplanar. This removed the single most serious systematic error arising from the solar detector reported by Hill and Stebbins (1975). Although these improvements increased the accuracy of the results, they altered the value of the systematic errors arising in the system from that reported by Hill and Stebbins, necessitating their reevaluation. The data are also being used to quantify the instrument's thermal characteristics and to adjust the computer programs which control the telescope.

2.5. Absolute Calibration of Telescope Field

The system for calibrating the primary field of the telescope was originally designed around the operation of a dual reference beam, with the second beam of light being generated from the primary laser beam by internal reflection in a prism. The angle between the two beams was defined by properties of the prism, with the angle's long-term stability directly dependent on the stability of the prism.

This system allowed the detection of changes in the field, but could not perform an absolute field calibration. This, together with difficulties in constructing a prism which would meet the necessary stability criteria, resulted in the replacement of the prism with a plane-reflecting grating to be manufactured using the modern lithographic techniques of the integrated circuit industry. This transition in thinking changed the system capabilities from a relative to an absolute calibration, with the added advantage that the grating only had to be stable over relatively short periods of time (that required to calibrate the telescope field and the grating).

Consider a grating of slit spacing d illuminated at normal incidence by a monochromatic laser source of wavelength λ . The resulting principal maxima are observed at angles θ_m given by

$$d \sin \theta_m = m\lambda \quad , \quad m = 0, \pm 1, \pm 2, \dots \quad (1)$$

where m is the order number. Thus the angle between two different principal maxima is determined absolutely by measuring the ratio, λ/d . Note that neither the absolute value of λ or d is required, only that d be measured in units of the laser source wavelength, λ .

A calibration scheme capitalizing on this feature would consist of the following. A grating with the appropriate d is placed in front of the telescope lens and a stabilized single mode He-Ne laser (6328 Å) is used as the light source to illuminate the grating and to generate the diffraction pattern. The locations of the relevant principal maxima are recorded by the solar edge detectors. The absolute angle separation of the recorded principal maxima is then determined by an independent measurement of the ratio, λ/d . This independent determination is made on a measuring engine whose table travel is measured via an interferometer which utilizes the same stabilized single mode laser which produced the original interference pattern.

There are several attractive features of this program. The grating and laser wavelength need only to be stable to the requisite accuracy for short periods of time (several hours). This obviates the need for the long-term stability of the prisms in the system first envisioned. The aberrations of the telescope optical system can be studied extensively with relative ease and requisite accuracy. At SCLERA, the required measuring engine to determine λ/d already exists in the experimental relativity program: the solar and stellar detectors and the interferometer used to record their separation.

The analysis of the systematic errors arising from the grating has been completed. The short-term thermal stability presents no particular problem. The most serious errors stem from aberrations in the wavefront of the laser beam introduced by a non-flat grating. The grating substrate cannot generally be manufactured to a sufficiently flat surface to eliminate this type of error. However, because of the properties of the relevant aberrations, it has been possible to design a series of measurements to identify their size and make appropriate corrections.

With the successful completion of the error analysis of the grating base system, the relaxation of the long-term stability requirement to only a few hours, and the change to an absolute angle measuring device, the decision was made to alter the basic dual beam calibration system to be built around a grating. There are several ways in which a grating might be fabricated. The two procedures that have been examined use holographic technology and the lithographic techniques previously mentioned. It appears the latter will lead to a grating better suited to our particular needs.

The next phase in this program is the construction of a grating. Apparatus exists in the Electrical Engineering Department for making integrated circuits and it is planned to manufacture the first grating there.

Results of the work have been reported by Hill (1980) and suggest that this calibration scheme has the dual advantages of practical implementation and a potential accuracy of 10^{-4} arcsec. This system may represent the "standard meter" for measuring angles.

2.6. The Image Sensor

The signal that is used to define the edge of the solar limb is presently derived from single detectors that scan a portion of the solar limb in a sinusoidal mode. In the search for long-term solar variability, the requisite stability must be inherent not only in the telescope and measuring engine, but also in the amplitude and degree of sinusoidal character of the scan. The introduction of a charge injected device (CID) camera will make it possible to obtain the information required to calibrate the amplitude scan and to study the spectral purity of the sinusoidal scan. During the funding period, the main effort was on the design and construction of an interface between the CID camera and an on-line microprocessor with its mass storage device. This interface has been constructed and is currently being tested.

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